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Brassica cover cropping: II. Effects on growth and interference of green bean (*Phaseolus vulgaris*) and redroot pigweed (*Amaranthus retroflexus*)

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Field studies have shown that weed density and biomass were lower in crops following incorporation of brassica cover crops compared with fallow but have not determined whether weed-suppressive effects are solely a consequence of reduced establishment, as evidenced in our companion paper, reduced growth of established plants, or both. In 2002 and 2003, canola and yellow mustard were seeded in early May, mowed in early July, and the residues incorporated. Green bean and redroot pigweed were then planted at fixed densities. Plant height and biomass were measured weekly; leaf area and biomass of component plant parts were measured at three harvests. Based on analysis of variance (ANOVA) at discreet sampling points, growth of redroot pigweed and green bean in monoculture or mixture were similar following fallow and incorporated brassica cover crops. However, based on aboveground biomass fitted to a Richards function, redroot pigweed growth in monoculture was reduced by the yellow mustard cover crop compared with fallow in both years ($P = 0.007$), but the magnitude of this effect was small; the canola cover crop did not affect growth ($P = 0.179$). Brassica cover crops did not reduce redroot pigweed growth when it was grown in mixture with green bean ($P \geq 0.382$). Redroot pigweed competition reduced green bean yield, but incorporated brassica cover crops did not affect green bean growth and yield, nor did they confer a competitive advantage to the crop. Thus, brassica cover crops may suppress the growth of established weed and crop plants, but the magnitude of suppression was less than previously documented for effects on weed establishment.

Nomenclature: Canola, 'Hyola', *Brassica napus* L.; redroot pigweed, *Amaranthus retroflexus* L. AMARE; yellow mustard, 'Idagold', *Sinapis alba* L.; green bean, 'Provider', *Phaseolus vulgaris* L.

Key words: Biofumigant, weed–crop competition, plant growth, Richards function, allelopathy.

Brassica cover crops, including canola (*Brassica napus* L.), rapeseed (*Brassica napus* L.), and mustard species (e.g., *Brassica juncea* L., brown and Indian mustard; *Brassica nigra* L., black mustard; and white or yellow mustard), have received considerable interest in recent years because of their potential contributions to pest management (Brown and Morra 1997; Haramoto and Gallandt 2004). All members of the Brassicaceae contain glucosinolates—sulfur-containing compounds that are enzymatically hydrolyzed to toxic breakdown products including isothiocyanates, ionic cyanates, and epinitriles (Brown and Morra 1997; Mithen 2001; Rosa et al. 1997). Bioassays conducted with plant residues containing these compounds, residue extracts, and isolated isothiocyanates demonstrated the following phytotoxic effects: inhibited seed germination (Brown and Morra 1996; Teasdale and Taylorson 1986), delayed seed germination (Brown and Morra 1996), reduced seedling emergence (Al-Khatib et al. 1997; Boydston and Hang 1995; Krishnan et al. 1998; Vaughn and Boydston 1997), and stunted seedling growth (Wolf et al. 1984). Field studies have confirmed lower mid- to late-season weed density and biomass in green pea (*Pisum sativum* L.) (Al-Khatib et al. 1997), soybean [*Glycine max* (L.) Merr.] (Krishnan et al. 1998), and potato (*Solanum tuberosum* L.) (Boydston and Hang 1995) grown following incorporation of brassica vegetation compared with fallow or, in some cases, incorporation of other cover crop residues.

The mechanisms by which brassica residues suppressed weeds in these field studies is not known. Based on controlled environment studies, likely mechanisms include inhibition of seed germination and seedling mortality resulting in lower weed density. Incorporated brassica residues may also delay weed establishment and reduce the vigor of established plants, reducing their competitive ability against crops. In support of the former mechanism, we report in a companion paper that, relative to fallow treatments, incorporated canola, rapeseed, and yellow mustard cover crops reduced establishment of a wide range of crop and weed bioassay species an average of 29% and delayed their emergence 1.8 d over 2 yr of study (Haramoto and Gallandt 2005).

There are several lines of evidence from greenhouse studies suggesting that incorporated brassica residues may suppress growth of plants that successfully establish. Biomass of 2-wk-old weed seedlings grown in soil with incorporated rapeseed, brown mustard, and white mustard residues was decreased by 16 to 71% compared with those grown in a control soil (Krishnan et al. 1998). Three-week-old hairy nightshade (*Solanum sarrachoides* Sendtner) and longspine sandbur [*Cenchrus longispinus* (Hack.) Fern.] seedling biomass, when grown in soil with rapeseed residue, was reduced by 83 to 90% compared with seedlings grown in soil without rapeseed residue, and 83% compared with seedlings grown in soil with potato residue (Boydston and Hang 1995).

Our objectives were to determine (1) how brassica cover crop residues would affect the growth of established plants in the field, (2) whether the effects of these residues were dependent on seed size of the test plant (Liebman and Davis 2000; Mohler 1996; Westoby et al. 1996), and (3) whether brassica cover crop residues would improve the competitive ability of larger-seeded crops. We selected two brassica species to study—canola, with relative low glucosinolate content (e.g., < 10 μmol total glucosinolate g^{-1} defatted seed meal), and yellow mustard, with relatively high glucosinolate content (e.g., 129 μmol total glucosinolate g^{-1} defatted seed meal; Brown et al. 1999). Redroot pigweed, a small-seeded weed (0.05 g 100 $seeds^{-1}$), and green bean, a large-seeded vegetable (31 g 100 $seeds^{-1}$), were planted into recently incorporated brassica residues and fallow, both alone and in mixture. We hypothesized that redroot pigweed growth would be suppressed by incorporated brassica cover crops, especially early in the season following the high-glucosinolate yellow mustard and that green bean growth would be unaffected by incorporated cover crop residues. We further expected to find that redroot pigweed grown with green bean would suffer more competitive losses following the brassica cover crops compared with fallow and that green bean grown with redroot pigweed would perform better following brassica cover crops compared with fallow, especially following the higher-glucosinolate yellow mustard, because of the suppression of redroot pigweed growth by the brassica cover crops.

Materials and Methods

Site and Experimental Design

Field studies were conducted at the University of Maine's Rogers Farm in Stillwater, ME. The 2002 field site, a Lamoine silt loam (fine, illitic, nonacid, frigid, Aeric Epiaquepts), with pH 6.1 and 3.9% organic matter, was cropped to potato the previous year. The 2003 field site, an Elmwood fine sandy loam (coarse-loamy over clayey, mixed over illitic, superactive, frigid Aquid Dystric Eutrudepts), with pH 6.8 and 3.8% organic matter, was previously cropped to cucurbits.

There were nine treatments in each year, a factorial combination of three cover crop treatments (fallow, yellow mustard, and canola) and three plant treatments (green bean alone, redroot pigweed alone, and the interspecific mixture). Plots in both years measured 3.3-m wide by 10.7-m long. Treatments were assigned to plots completely randomly in 2002 but were arranged in blocks in 2003 to account for an apparent gradient in soil texture. Each treatment was replicated four times in each year.

Field Practices

Soil preparation in 2002 consisted of disking followed by packing; in 2003, the field was harrowed and then packed. Canola and yellow mustard were sown at 13 kg ha^{-1} using a Brillion[1] seeder on May 9, 2002 and May 16, 2003. No fertilizer was applied before cover crop seeding. To avoid further soil disturbance and maintain a similar disturbance regime to the cover cropped plots, weeds were controlled in fallow plots by periodic cutting of small seedlings with a powered string trimmer. Herbicides were not applied to any plots in either year.

Before incorporation, two 0.25-m^2 quadrats were sampled from each plot to estimate cover crop aboveground biomass; plant material was dried at 65 C for 7 d and weighed. On July 9, 2002 and July 10, 2003, cover crops were mowed with a flail mower, and their residues were incorporated to a depth of 15 cm with two passes of a rotary tiller. Yellow mustard and canola were mowed and incorporated at late flowering, i.e., after they had set seed but before seed maturation (Harper and Berkenkamp 1975). This stage was selected for incorporation because it typically contains maximum glucosinolate content (Fieldsend and Milford 1994). Although glucosinolate concentration can be diluted by increasing plant biomass and glucosinolates move from the leaves to the stems to the pods, the increased biomass leads to maximal glucosinolate content (product of concentration and biomass) in the whole plant during later flowering and early mid-pod set (Fieldsend and Milford 1994). Following the first pass, ammonium nitrate and ground triple super phosphate fertilizers were broadcast-applied to all treatments in both years according to soil test recommendations for green bean, with 35 kg nitrogen (N) ha^{-1} applied in both years, and 70 and 80 kg phosphorus (P) ha^{-1} applied in 2002 and 2003, respectively.

Green bean and redroot pigweed were planted immediately following residue incorporation. Green bean was planted with a four-row planter on 81.3-cm centers. Redroot pigweed was hand-seeded in a 1-cm-deep trench created using the edge of a hardwood stake; seeds were sprinkled into this trench, covered with soil, and firmly packed. These trenches were located 5 cm to the east of the green bean rows in 2002 and 5 cm to the west of the green bean rows in 2003. To account for reduced emergence following the brassica cover crops (Haramoto and Gallandt 2005), redroot pigweed was seeded at a high density, and seedlings were thinned at 3 and 5 wk after planting to a final target density of 24 plants m^{-2} or a seedling every 5.1 cm. In 2002, the first planting of green bean in canola and yellow mustard cover crop treatments was destroyed by seed corn maggot (*Delia platura* Meigen); green beans were subsequently removed by hand after it became apparent that the stands would not recover. The seed corn maggot, however, did not affect redroot pigweed. Because our foremost interest was related to the effects of the incorporated brassica residues on weed growth, the initial stand of redroot pigweed was left intact. Green beans were replanted with minimal soil disturbance using an Earthway Precision Garden Seeder[2] on July 24, 2002, 2 wk after the redroot pigweed was seeded. A diazinon[3] soil drench was applied at 3 L ai ha^{-1} to protect green bean seeds from further seed corn maggot injury. For consistency, this staggered planting was repeated in 2003, using the same planting methods for green bean and redroot pigweed growth. This resulted in mixed stands of uneven-aged species, and we acknowledge that a farmer would never plant a crop into such an advanced stand of weeds. However, because release of phytotoxic glucosinolate hydrolysis products was presumably highest immediately following residue incorporation (Morra and Kirkegaard 2002), this experimental protocol allowed us to examine the maximum effect of freshly incorporated brassica residues on redroot pigweed. Although the delay in green bean planting would underestimate the effects of brassica cover crops on green bean, the system assured a robust effect of interspecific interference given the initial size advantage of the redroot pigweed, i.e., a "worst case" scenario. Lastly, several authors have argued that stresses such as those imposed by incorporated residues would either fail to, or minimally, affect the large-seeded green bean (Liebman and Davis 2000; Mohler 1996; Westoby et al. 1996).

Plant Sampling and Data Collection

Beginning 20 and 17 days after green bean planting in 2002 and 2003, respectively, plants in each plot were destructively harvested on a weekly basis. Only plants from the center two rows were harvested; randomly assigned harvest areas were 0.6 m long (1 m^2) and separated by a 0.6-m buffer, with 1.5 m between the north–south plot edges and the harvest areas.

Aboveground biomass was collected by clipping plants at the soil surface. Coarse root biomass was sampled by digging to a depth of 20 cm and gently pulling all plants from the soil; soil was washed from roots over a screen. The height of each sampled plant was measured from the soil surface to the highest growing point. Plants were bulked, bagged, and dried at 65 C for 7 d and then weighed. At harvests 1, 3, and 6 of each year, sampled plants were separated into roots, stems, leaves, and reproductive material. Harvest 1 was 34, and 20 days after planting (DAP) in 2002 and 32 and 17 DAP in 2003 for redroot pigweed and green bean, respectively. Harvest 3 was 47 to 48 and 33 to 34 DAP in 2002 and 46 to 47 and 31 to 32 DAP in 2003 for redroot pigweed and green bean, respectively. The sixth and final harvest was 68 to 70 and 55 to 56 DAP in 2002 and 67 to 69 and 52 to 54 DAP in 2003 for redroot pigweed and green bean, respectively. These component samples were dried and weighed; leaf area measurements[4] were also made on these dates. Marketable green beans (> 6.5 cm long and free of external defects) were collected from a final 1.5-m^2 harvest area periodically until plants were frost-killed.

Data Analysis

All plant growth parameters, including height, biomass, leaf area and marketable yield, were subjected to analysis of variance (SYSTAT 2003). To examine the differences between plant growth following brassica cover crops and fallow, data from green bean or redroot pigweed monocultures were analyzed using only cover crop treatment as a factor. We also examined the effects of brassica cover crops on plant growth when they were grown with other plants by analyzing data from green bean and redroot pigweed grown in mixture.

Aboveground plant biomass was fitted to a modified Richards function:

$$W = A(1 + e^{B-KT})^{-1/N} \quad [1]$$

using GraphPad Prism software[5] where W is plant biomass; A is the upper asymptote; B is the time lag or delay; K is the slope; N is the height of the inflection point; and T is time (Causton et al. 1978; Miles et al. 2002). The Richards function has both the interpretable parameters and the flexibility to fit a wide range of sigmoidal curves (Miles et al., 2002).

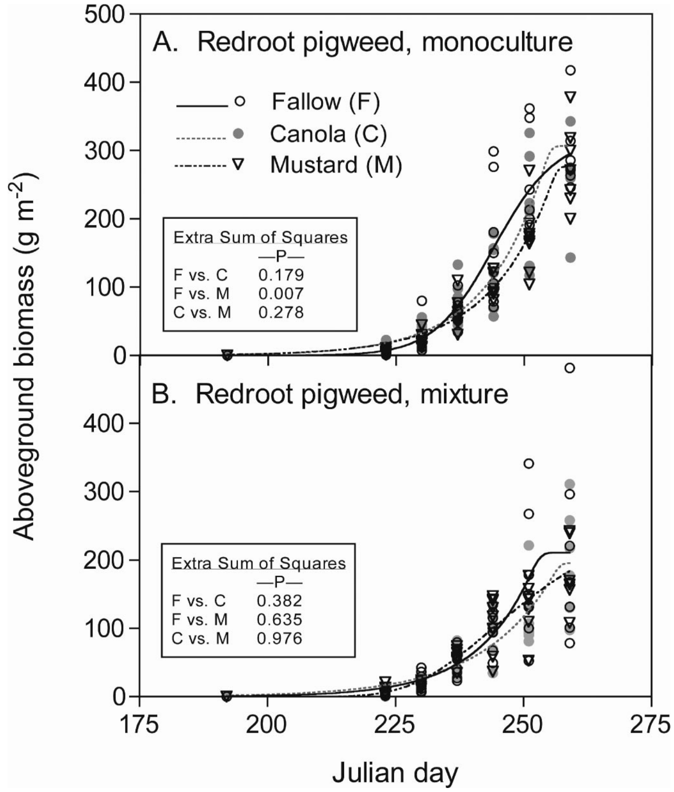

FIGURE 1. Growth of redroot pigweed in monoculture (A), or in mixture with green bean (B), following fallow, incorporated canola, or incorporated yellow mustard cover crops. Data plotted are values for individual replicates in 2002 and 2003 (n = 8); lines are the best fit of Richards function to each cover crop treatment. Extra sum of squares tested the null hypothesis that a single model best fit the data sets being compared; P < 0.05 indicated separate models best described the data.

Treatment effects on growth throughout the season were based on extra sum-of-squares comparisons of the Richards function fit to combined, and then individual, data sets (Motulsky and Christopoulos 2003; Ratkowsky 1983). Lindquist et al. (1996) provide a detailed description of the extra sum-of-squares approach to comparing estimated parameters of weed density and crop yield loss relationships. In general, the extra sum-of-squares approach uses an F test to compare two treatments. For example, to test the hypothesis that redroot pigweed growth, grown in monoculture, is similar following fallow compared with an incorporated mustard cover crop (i.e., a single growth curve best fits the data for both treatments), curves for the two data sets are first fit separately. Next, the data are combined, and one curve is fit to the pooled data. Lastly, the sum of the sum of squares for the separate curves is compared with the sum of squares for the combined analysis using a calculated F ratio. The corresponding P value may be determined using tables found in many statistics books or using the "FDST" function in Excel. A significant P value indicates that the curves fit to the two data sets are different; this comparison considers the entire curve, but subsequent analyses can be performed to test for effects on individual fit parameters (see Lindquist et al. 1996).

Table 1. Effect of preceding cover crop treatments on biomass allocation of redroot pigweed grown in monoculture and in mixture with green beans. Plants were harvested 68 to 70 d after planting in 2002 and 67 to 69 d after planting in 2003.

Competition and preceding cover crop	Root		Stem		Leaves		Reproductive		Leaf area		Plant height	
	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003
	$g\ m^{-2}$								$m^2\ m^{-2}$		cm	
Monoculture												
Fallow	21.9	20.1	136.2	126.2	79.3	80.9	78.7	67.1	1.27	1.57	72.9	62.8
Canola	21.3	25.9	121.3	158.1	71.6	93.8	75.9	67.7	1.07	1.32	72.8	66.1
Mustard	17.6	23.0	100.6	135.2	61.8	84.0	69.6	68.3	0.94	1.33	67.2	64.6
Mixture												
Fallow	17.2	12.9	104.3	75.7	60.7	43.4	59.1	49.3	0.94	0.81	63.4	52.9
Canola	15.5	15.5	84.4	92.4	53.0	52.7	58.8	54.2	0.77	0.72	63.4	57.8
Mustard	13.4	15.0	78.9	85.4	47.5	51.7	50.0	45.2	0.75	0.78	66.2	59.4
ANOVA	P											
Competition	0.142	0.021	0.190	0.027	0.110	0.033	0.027	0.057	0.157	< 0.001	0.342	0.158
Preceding cover crop	0.570	0.589	0.541	0.684	0.463	0.688	0.602	0.926	0.503	0.643	0.981	0.761
Interaction	0.978	0.920	0.960	0.949	0.974	0.941	0.990	0.905	0.945	0.859	0.849	0.933

Results and Discussion

Cover Crop Growth

In 2002, an average of 353 and 319 g m^{-2} of yellow mustard and canola dry biomass, respectively, were incorporated before planting redroot pigweed and green bean. In 2003, 126 and 129 g m^{-2} of yellow mustard and canola dry biomass, respectively, were incorporated. Lower cover crop biomass production in 2003 was attributed to a period of unusually cool, wet, cloudy weather following planting. Relative to effects on emergence (Haramoto and Gallandt 2005), plant growth response to the cover crop treatments might be underestimated in that year. However, although this amount of cover crop biomass was less than the 420 to 450 g m^{-2} of dry white mustard (*Sinapis alba* L.) biomass incorporated by Al-Khatib et al. (1997) before planting green pea, it was greater than, or comparable to, the 50 to 139 g m^{-2} dry white mustard biomass that Krishnan et al. (1998) incorporated before planting soybean. Both of these studies reported less weed pressure in subsequent crops following the incorporation of brassica residues compared with fallow. The weed species in these experiments included redroot pigweed and common lambsquarters (*Chenopodium album* L.) in addition to several other broadleaf and grass species.

Plant Density

Redroot pigweed density averaged 23 ± 4 plants m^{-2} in 2002 and 22 ± 3 plants m^{-2} in 2003 (mean ± SD of all treatments and harvest dates). Green bean density averaged 22 ± 5 plants m^{-2} in 2002 and 18 ± 4 plants m^{-2} in

Table 2. Effect of preceding cover crop treatments on biomass allocation of green bean grown in monoculture and in mixture with green bean. Plants were harvested 54 to 56 d after planting in 2002 and 52 to 54 d after planting in 2003.

Competition and preceding cover crop	Root		Stem		Leaves		Reproductive[a]		Leaf area		Plant height	
	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003
	$g\ m^{-2}$								$m^2\ m^{-2}$		cm	
Monoculture												
Fallow	4.80	9.88	19.7	53.2	47.5	101.9	3.46	10.2	0.88	1.64	24.6	36.1
Canola	6.66	9.97	22.0	39.2	53.4	86.5	6.61	7.86	1.01	2.06	25.1	33.0
Mustard	5.37	8.55	17.5	40.1	44.2	87.2	4.27	8.14	0.93	1.76	23.9	34.0
Mixture												
Fallow	3.94	8.03	12.7	35.1	25.1	66.4	4.20	8.45	0.60	1.08	23.3	35.1
Canola	3.92	6.81	11.7	25.2	26.1	53.2	3.67	6.81	0.58	1.41	22.6	32.9
Mustard	3.96	6.55	10.8	22.9	22.9	44.8	2.64	6.01	0.58	0.98	22.2	32.6
ANOVA	P											
Competition	0.002	0.004	< 0.001	0.001	< 0.001	< 0.001	0.051	0.082	0.002	< 0.001	0.298	0.568
Preceding cover crop	0.292	0.284	0.506	0.037	0.409	0.145	0.088	0.107	0.876	0.108	0.893	0.299
Interaction	0.273	0.706	0.708	0.912	0.783	0.938	0.070	0.880	0.810	0.850	0.957	0.928

[a] Excludes marketable beans.

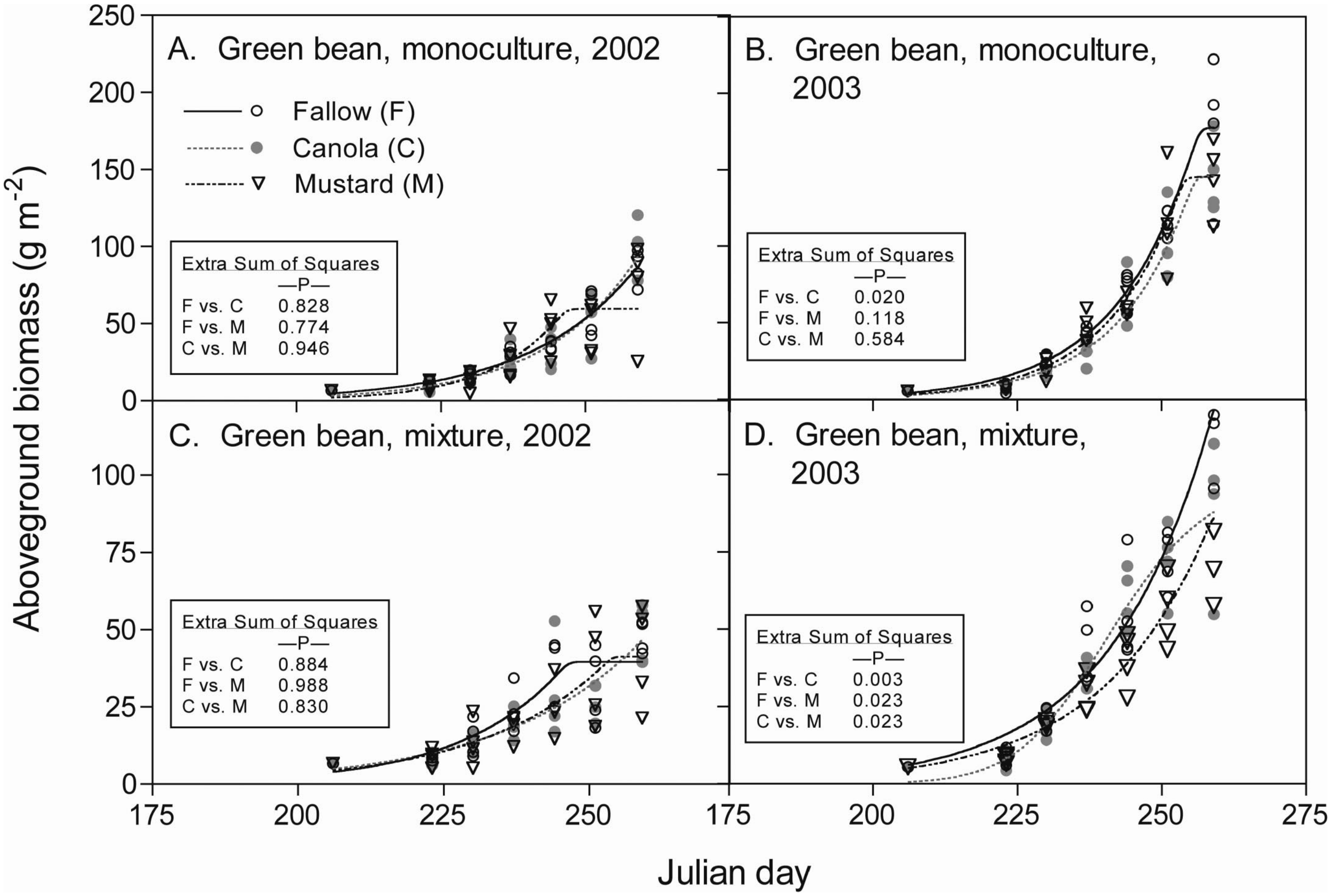

FIGURE 2. Growth of green bean in monoculture in 2002 (A), or 2003 (B), and growth of green bean grown in mixture with redroot pigweed in 2002 (C), or 2003 (D) following fallow, incorporated canola, or incorporated yellow mustard cover crops. Data plotted are values for individual replicates (n = 4); lines are the best fit of Richards function to each cover crop treatment. Extra sum of squares tested the null hypothesis that a single model best fit the data sets being compared; $P < 0.05$ indicated separate models best described the data.

2003. Because the effects of incorporated cover crop residues on establishment was the focus of a related but separate field study (Haramoto and Gallandt 2005), treatment effects on green bean or pre-thinning redroot pigweed densities were not measured in these experiments.

Redroot Pigweed Growth and Interference by Green Bean

Preliminary extra sum-of-squares comparisons of redroot pigweed growth in individual treatments over years indicated that a single model would best fit both years of data; this was true for redroot pigweed following each of the three cover crop treatments in both monoculture and mixture. Subsequent comparisons were made using data sets combined over years (Figure 1).

Grown in monoculture, redroot pigweed biomass accumulation was best fit to a single model for fallow and canola cover crop treatments (Figure 1A; P = 0.179). In other words, we did not detect an effect of cover crop treatment on growth, which, therefore, was best represented by a single curve for both treatments. This was not the case for growth following mustard. Compared with fallow, growth following yellow mustard cover crop treatments was, as expected, reduced and best described by a separate model (P = 0.007). Although we expected growth of redroot pigweed following canola to be intermediate relative to the fallow and yellow mustard cover crop treatments, it was actually similar following canola and yellow mustard cover crops (P = 0.278).

Although the yellow mustard cover crop suppressed subsequent redroot pigweed growth in monoculture (Figure 1A), this effect was not detected when redroot pigweed was grown in mixture with green bean (Figure 1B). This fails to support our original hypothesis that incorporated yellow mustard residues would suppress redroot pigweed growth thereby conferring a competitive advantage to the green bean. We expected that the delay in green bean planting would reduce the competitive effect of green bean on redroot pigweed. This would have explained a similar degree of growth reduction caused by the yellow mustard residues in both monoculture and mixture, but it does not explain the lack of cover crop treatment effects when plants were grown in mixture. We suggest that the variation in redroot pigweed growth caused by yellow mustard residues is relatively small compared with unexplained variation in growth.

The suppression of redroot pigweed biomass accumulation due to incorporated yellow mustard residues, although evident by growth analysis of the monoculture plants, was not detected when several components of plant growth were subjected to analysis of variance (ANOVA). At the sixth and final harvest, 67 to 70 DAP, for example, root, stem, leaf, and reproductive biomass of redroot pigweed grown in monoculture, as well as plant height and leaf area, were unaffected by cover crop treatment in both years (Table 1). Although differences in these parameters were often detected between monoculture-grown and mixture-grown redroot pigweed, the interaction between growth regime and preceding cover crop did not affect any parameter in either year (Table 2). Redroot pigweed biomass allocation was likewise unaffected by cover crop treatment at the first harvest (32 to 34 DAP) or the third harvest (45 to 47 DAP).

Green Bean Growth and Interference by Redroot Pigweed

Whereas preliminary extra sum-of-squares comparisons indicated that a single model would best fit both years of redroot pigweed data, this was not true for any of the green bean treatment combinations. Compared with 2003, lower green bean biomass in 2002 was likely the result of extremely low precipitation during August of 2002 (15 mm; 30-yr average for August, 82 mm). In subsequent comparisons of green bean growth, years were analyzed separately (Figure 2).

In 2002, green beans grown in monoculture were unaffected by cover crop treatments (Figure 2A), but in 2003, canola suppressed green bean growth in comparison with fallow ($P = 0.020$; Figure 2B). Although the fitted Richards function for green bean following incorporated yellow mustard residues was consistently below that of the fallow treatment, these data were best fit by a single model ($P = 0.118$) indicating that the treatments were not different.

Cover crop treatment effects on growth of green bean in mixture with redroot pigweed were similar to results for green bean grown in monoculture: growth was unaffected by cover crop treatment in 2002 (Figure 2C) but suppressed by brassica cover crop residues in 2003 (Figure 2D). In 2003, canola and yellow mustard residues both reduced green bean growth compared with fallow treatments, but examination of the growth curves indicated generally similar growth of green bean following fallow and canola until the final harvest; growth following yellow mustard was reduced relative to the fallow treatment throughout the season (Figure 2D).

Like redroot pigweed, biomass allocation in green bean was similar across cover crop treatments. For instance, with the exception of stem biomass in 2003, biomass of all component parts, leaf area, and plant height were unaffected by cover crop treatment at the final harvest (52 to 56 DAP) in both years (Table 2). Cover crop treatments consistently failed to affect biomass allocation at other harvest dates (data not shown) or when green bean was grown in mixture with redroot pigweed in either year (Table 2).

Green Bean Yield

Although the presence of competing plants generally decreased plant biomass, height, leaf area, and growth rate, the interaction between competition and cover crop treatment was not significant for any of the growth parameters measured (data not shown). Green bean yield was reduced by redroot pigweed competition ($P < 0.001$ in both years; Figure 3). Despite our ability to detect changes in green bean growth following brassica cover crops (Figure 2B and 2D), these effects on biomass accumulation were not reflected in the marketable green bean yield (Figure 3).

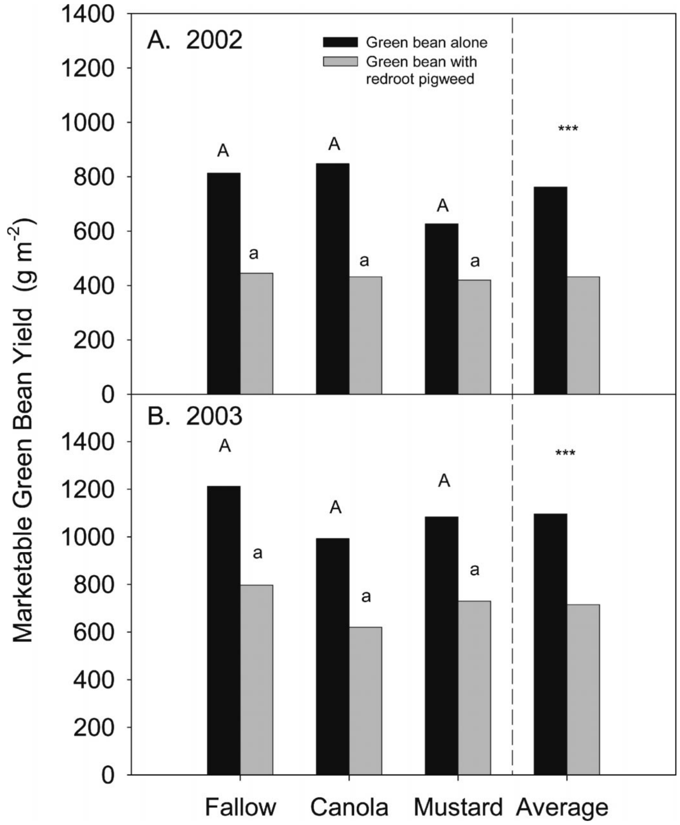

FIGURE 3. Marketable green bean yield for green bean grown in monoculture or in mixture with redroot pigweed in 2002 (A), or 2003 (B), following fallow, incorporated canola, or incorporated yellow mustard cover crops. Within monoculture or mixture treatments, bars labeled with common upper- or lowercase letters were not significantly different ($P > 0.05$).

Conclusion

Although comparison of season-long growth curves for redroot pigweed biomass accumulation confirmed that incorporated yellow mustard cover crops may suppress subsequent plant growth, this effect was not of sufficient magnitude to be detected when plants were grown in interspecific mixture nor when biomass allocation was subjected to ANOVA. Furthermore, because redroot pigweed biomass was unaffected by an interaction between cover crop treatment and competitive environment, incorporated cover crops apparently did not mediate interspecific interference. Thus, although brassica green manures may suppress weeds in different field settings (Al-Khatib et al. 1997; Boydston and Hang 1995; Krishnan et al. 1998), our results suggest that the mechanism responsible for this suppression is foremost related to effects on weed establishment (Haramoto and Gallandt 2005).

Sources of Materials

[1] Brillion "Sure Stand" Seeder, model SS-60-01, Brillion Farm Equipment, 200 Park Ave., Brillion, WI 54110.

[2] Seeder, Earthway Products, 1009 Maple St., Bristol, IN 46406.

[3] Diazinon AG500, 47.5% diazinon; Southern Agricultural Insecticides, Inc. P.O. Box 429, Palmetto, FL 34221.

[4] Delta-T Area Measurement System, model CB-7851, Delta-T Devices, Ltd. 128 Low Rd. Burwell, Cambridge, CB5 0EJ U.K.

[5] GraphPad Prism Version 4.0, GraphPad Software, Inc., 11452 El Camino Real, #215, San Diego, CA 92130.

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Literature Cited

Al-Khatib, K., C. Libbey, and R. Boydston. 1997. Weed suppression with *Brassica* green manure crops in green pea. Weed Sci. 45:439–445.

Boydston, R. and A. Hang. 1995. Rapeseed (*Brassica napus*) green manure crop suppresses weeds in potato (*Solanum tuberosum*). Weed Technol. 9:669–675.

Brown, P. D. and M. J. Morra. 1996. Hydrolysis products of glucosinolates in *Brassica napus* tissues as inhibitors of seed germination. Plant Soil 181:307–316.

Brown, P. D. and M. J. Morra. 1997. Control of soil-borne plant pests using glucosinolate-containing plants. Adv. Agron. 61:167–231.

Brown, A. P., J. Brown, and J. B. Davis. 1999. Developing high glucosinolate cultivars suitable for bio-fumigation from intergeneric hybrids. *in* N. Wratten and P. A. Salisbury, eds. Proceedings of the 10th International Rapeseed Conference, Canberra, Australia. Gosford, New South Wales: The Regional Institute Ltd. (May 2005; www.regional.org.au/au/gcirc/).

Causton, D. R., C. O. Elias, and P. Hadley. 1978. Biometrical studies of plant growth, I: the Richards function, and its application in analyzing the effects of temperature on leaf growth. Plant Cell Environ. 1:163–184.

Fieldsend, J. and G. Milford. 1994. Changes in glucosinolates during crop development in single- and double-low genotypes of winter oilseed rape (*Brassica napus*), I: production and distribution in vegetative tissues and developing pods during development and potential role in the recycling of sulphur within the crop. Ann. Appl. Biol. 124:531–542.

Haramoto, E. R. and E. R. Gallandt. 2004. Brassica cover cropping for weed management: a review. Renew. Agric. Food Syst. 19:187–198.

Haramoto, E. R. and E. R. Gallandt. 2005. Brassica cover cropping: I. Effects on crop and weed establishment. Weed Sci. 53:695–701.

Harper, F. R. and B. Berkenkamp. 1975. Revised growth-stage key for *Brassica campestris* and *B. napus*. Can. J. Plant Sci. 55:657–658.

Krishnan, G., D. L. Holshouser, and S. J. Nissen. 1998. Weed control in soybean (*Glycine max*) with green manure crops. Weed Technol. 12: 97–102.

Liebman, M. and A. S. Davis. 2000. Integration of soil, crop, and weed management in low-external-input farming systems. Weed Res. 40: 27–47.

Lindquist, J. L., D. A. Mortensen, S. A. Clay, R. Schmenk, J. J. Kells, K. Howatt, and P. Westra. 1996. Stability of coefficients in the corn yield loss—velvetleaf density relationship across the North Central U.S. Weed Sci. 44:309–313.

Miles, J. E., O. Kawabata, and R. K. Nishimoto. 2002. Modeling purple nutsedge sprouting under soil solarization. Weed Sci. 50:64–71.

Mithen, R. 2001. Glucosinolates and the degradation products. Pages 214–262, *in* J. Callow, ed. Advances in Botanical Research, Vol. 35. New York: Academic Press.

Mohler, C. L. 1996. Ecological basis for the cultural control of annual weeds. J. Prod. Agric. 9:468–474.

Mojtahedi, H., G. Santo, J. Wilson, and A. N. Hang. 1993. Managing *Meloidogyne chitwoodi* on potato with rapeseed as green manure. Plant Dis. 77:42–46.

Morra, M. J. and J. A. Kirkegaard. 2002. Isothiocyanate release from soil-incorporated *Brassica* tissues. Soil Biol. Biochem. 34:1683–1690.

Motulsky, H. J. and A. Christopoulos. 2003. Fitting Models to Biological Data Using Linear and Nonlinear Regression: A Practical Guide to Curve Fitting. San Diego, CA: GraphPad Software.

Ratkowsky, D. A. 1983. Nonlinear Regression Modeling. New York: Marcel Dekker. Pp. 135–154.

Rosa, E., R. Heaney, G. Fenwick, and C. Portas. 1997. Glucosinolates in crop plants. Pages 99–215, *in* J. Janick, ed. Horticultural Reviews, Vol. 19. New York: J Wiley.

[SYSTAT] Systat Software Inc. 2003. Release 10.2.01, Richmond, CA: Systat Software Inc.

Teasdale, J. R. and R. B. Taylorson. 1986. Weed seed response to methyl isothiocyanate and metham. Weed Sci. 34:520–524.

Vaughn, S. F. and R. A. Boydston. 1997. Volatile allelochemicals released by crucifer green manures. J. Chem. Ecol. 23:2107–2116.

Westoby, M., M. Leishman, and J. Lord. 1996. Comparative ecology of seed size and dispersal. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 351: 1309–1318.

Wolf, R. B., G. F. Spencer, and W. F. Kwolek. 1984. Inhibition of velvetleaf (*Abutilon theophrasti*) germination and growth by benzyl isothiocyanate, a natural toxicant. Weed Sci. 32:612–615.

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